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PERFORMANCE CHARACTERISTICS
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FIELD OPERATION
of
TWO RAINFALL SIMULATORS

by

Earl L. Neff

U. S. Department of Agriculture

Agricultural Research Service

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PERFORMANCE CHARACTERISTICS AND FIELD OPERATION OF TWO RAINFALL SIMULATORS

By
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Introduction

Rainfall simulators have been used for many years to study erosion, infiltration, and runoff from both crop and rangeland. The Bureau of Land Management (BLM) designed a rainfall simulation project in 1976-1977 to provide district office staff with data to evaluate and predict the effects of Livestock Management Systems on infiltration and erosion. Large plot (about 3000 ft^2) sprinkler-type studies were conducted with a version of the Colorado State University rainfall simulator (CSUS) (Holland, 1969) from 1978 through 1980. At the same time, BLM contracted with the U.S. Geological Survey (USGS) to provide large plot sprinkler-type rainfall simulation data to use in calibrating a rainfall-runoff model for surface mined lands (Lusby, 1977). In 1981, the BLM large-plot simulator was modified to be used on 400 ft^2 plots in conjunction with salinity studies in east-central Utah and grazing studies at Saval Ranch, Nevada. Also in 1981, BLM used small drop-former simulators in studies of hydrologic effects of grazing at Saval Ranch and at Woodside, Utah.

Because of continued interest in rainfall simulation, the BLM requested an expansion of Interagency Agreement YA-515-IA6-3 with the USDA Agricultural Research Service (ARS) to evaluate the performance and operational characteristics of the CSUS and to attempt to develop a more cost and water-efficient simulator for BLM field use. The interagency agreement terminated in FY 1981 and a new agreement between the BLM and the ARS was developed for FY 1982. This is the final report of that agreement.

This report is divided into the major divisions: Introduction which contains the history and background of the study; Simulator Design and Performance which discusses design criteria and test performace for both the Field Efficient Simulator (FES) and the portable version of the Colorado State University Simulator (CSUS); Field Operations which contains a description of the methods and procedures I used during the field use of the rainfall simulators; and Bibliography which lists literature cited in the report. In addition, throughout the report I have included comments, informal observations, and suggestions based on my experience in constructing, testing, and operating the simulators. This report is not meant to be a purely scientific treatment of the subject, but is intended to provide background information and operating suggestions to those who are charged with the responsibility for construction and field use of these simulators. Not all of my comments are scientifically verifiable, but they are intuitive knowledge gained from observations made during the course of this study.

Simulator Design and Performance

Field Efficient Simulator (FES):

The original objective was to develop a rainfall simulator with the following characteristics:

1. Inexpensive to construct, operate, and maintain.
2. Utilizes a plot with minimum dimensions of 6 feet wide and 20 feet long.
3. Applies simulated rainfall at rates of 1 to 4 inches per hour.
4. Has drop size distribution and kinetic energy similar to natural rainfall.
5. Uses no more than 400 gallons of water per run.

Several decisions were made to meet these design criteria:

1. All components would be stock items with off-the-shelf availability. This eliminated design and testing expenses as well as charges for special fabrication.
2. Sprinkler heads would be of a design that distributes water in a flat, 180° fan shape. This would eliminate the inefficiency of 360° distribution.
3. Sprinkler heads would distribute water in a 10-foot radius of the riser.
4. The plot size tested would be 6 feet wide and 30 feet long. This size could be accomodated with nine sprinklers, four on one side of the plot and five on the other.
5. The design would be flexible so that longer plots could be accomodated by adding additional sprinkler risers.
6. The criteria of high rainfall application rates and low water use were incompatable when considering the length of time required for a run. The target of 400 gallons of water per run was therefore removed as a criterion.
7. Flow control would be achieved by adjustable pressure regulators on each sprinkler riser.

The first step was the selection of a sprinkler head. We ordered about 10 different designs from different manufacturers for preliminary testing. Most of these were so-called "shrub heads" used for irrigating low-growing shrubs and bushes. One characteristic of shrub head sprinklers is a spray with relatively small drop sizes. A sprinkler manufactured by the Rain Jet Corporation (*) proved the most satisfactory. While this sprinkler is used for irrigation, it was originally designed to produce rain on motion picture sound stages. Photographic effects required larger drops than those produced by ordinary shrub heads. The drop sizes and the distribution of sizes produced by Rain Jet head RN-3 compared favorably with natural rain (Fig. 1).

The RN-3 sprinkler head was selected for use and the rainfall simulator was assembled as shown on Fig. 2.

We used 2½-inch main line and 2-inch supply lines because these sizes were available from another simulator. These sizes are much larger than necessary. For the layout shown in Fig. 2, a main supply line of 1½ inches and supply lines of 1 inch should be more than adequate. Significant savings can be realized by keeping these lines as small as possible because the cost of hose and pipe fittings increases rapidly with size.

(*) Trade names are used in this report for information only and do not constitute an endorsement by the U. S. Department of Agriculture or the Agricultural Research Service.

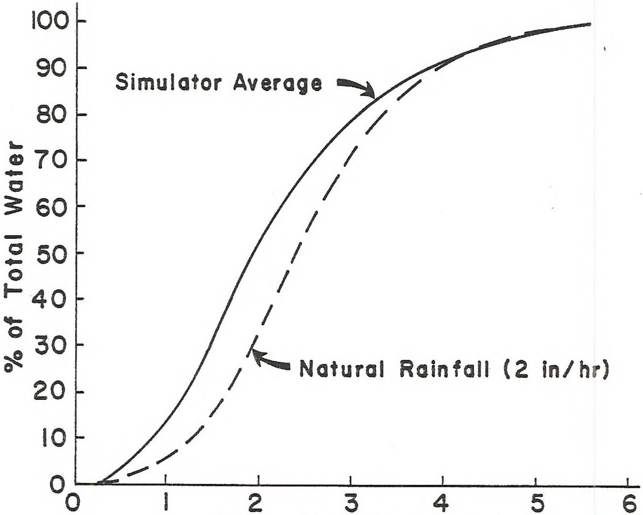
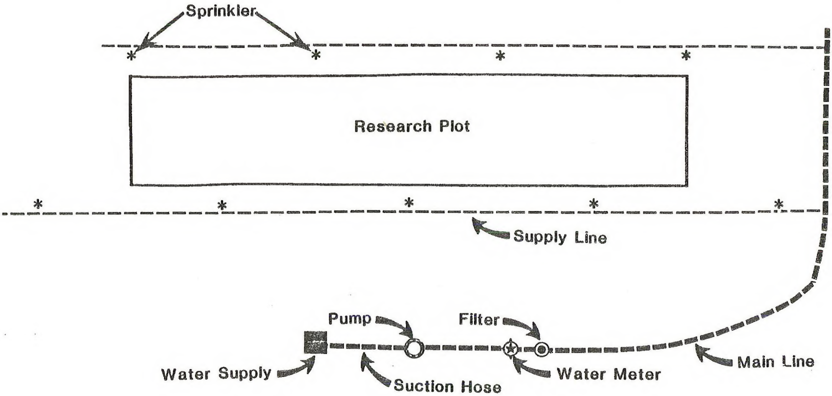


Figure 1. Drop size distribution of natural rainfall at 2 in/hr intensity and average drop size distribution for the field efficient simulator (FES).

Figure 2. Physical layout of the field efficient simulator (FES).



Sprinkler risers were assembled as shown on Fig. 3. Table 1 lists the bill of materials for a single riser.

TABLE 1

Bill of Materials for Sprinkler Riser
Field Efficient Simulator

Item	Description	Source of Supply
1	Spike, 3/4" x 18" rolled steel	Shop made
2	Plate, 1/4" x 6" x 6"	Shop made
3	Male side of 1/2" pipe union	Local purchase
4	Female side of 1/2" pipe union	Local purchase
5	Nipple, 1/2" x 4"	Local purchase
6	Tee, 1/2" x 1/2" x 3/4"	Local purchase
7	3/4" HT with 3/4" hose shank	Local purchase
8	Hose clamp	Local purchase
9	Industrial grade hose, 3/4" x 24"	Local purchase
10	Quick-connect coupler with hose shank, 3/4"	OPW Kamlok, Dover Corp., Cincinnati, Ohio Mil-C-27487
11	Adjustable ball fitting, 1/2" x 1/2"	Spraying Systems Co., Wheaton, IL
12	Nipple, 1/2" x 4"	Local purchase
13	Pressure regulator, 1/2"	Spraying Systems Co., Wheaton, IL
14	Pressure gage, liquid filled, 0-60 psi range	Marsh Instrument Co., Skokie, IL
15	Pipe, 1/2" x 108"	Local purchase
16	Coupling, 1/2"	Local purchase
17	Sprinkler head, 1/2", Mdl.RN-3	Rain Jet Corp., Burbank, CA

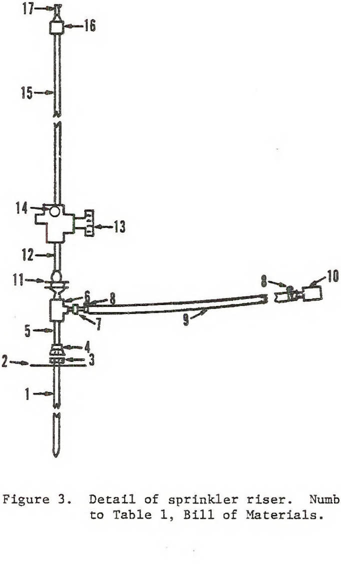


Figure 3. Detail of sprinkler riser. Numbers refer to Table 1, Bill of Materials.

At first inspection, some of the components shown on Fig. 3 and listed in Table 1 may appear to be elaborate and costly. Several years' field experience in simulator operation has demonstrated that component cost is only a fraction of the total costs for labor and travel for field work. Quality components that increase the ease with which a simulator is erected, or that reduce the number of malfunctions that cause runs to be interrupted or aborted are cost savers in the long run. An example is item 10, Kamlok quick connectors. In 1980, a set of these connectors cost nearly $15, about five to seven times the cost of quick connectors available in the local hardware stores. Prior to installing the Kamlok connectors, we experienced interuptions due to connectors blowing off or leaking during simulator runs. We experienced no connector failures after the Kamloks were installed. Another example is item 11, the adjustable ball fitting. This fitting cost about $10 in 1980, but it eliminated the problem of establishing and maintaining vertical alignment of the riser pipe on sloping ground. Still another example is item 14, the liquid-filled gage that cost nearly $20 compared to about $4 for ordinary gages. The liquid-filling damps needle vibrations and permits more accurate pressure measurements and the sealed case prevents water from leaking in and damaging the internal mechanism. All these items are more costly initially, but each eases installation, prevents downtime, and increases measurement accuracy, all of which decrease operations labor costs.

Various tests were run with the rainfall simulator to determine operating characteristics. These tests were run with different sprinkler head pressures as measured at the outlet of the pressure regulator on each riser and with different supply line pressures as measured at the pump outlet.

Flow Rate: We measured flow rate for the simulator at sprinkler head pressures of 10, 15, 20, 25, 30, 35, 40, 45 and 50 psi and at supply line pressures of 50, 60, and 70 psi. Results are shown on Fig. 4 which indicates that flow rates increased with increasing sprinkler head pressures, and that flow rates were not sensitive to variations in supply line pressure when the supply line pressure was at least 10 psi greater than the regulator setting.

Areal Distribution: Areal distribution was measured under different conditions of sprinkler head pressure and supply line pressure by a network of non-recording rain gages on and surrounding the research plot. Results were variable, but mostly showed non-uniform areal distribution over the plot. The location of the rain gages catching either high or low amounts was not related to either sprinkler head or supply line pressure. The non-uniform areal distribution on the plot appeared to result from a combination of wind effects during different runs and the location of the sprinkler risers with respect to the plot borders. When the simulator was designed, I assumed a 180° uniform distribution from each sprinkler. Consequently, the risers were placed 1 foot outside the plot border. Tests made after the problem with areal distribution arose indicate that the sprinklers do not produce a uniform 180° pattern. Instead of being fan shaped, the area of uniformity was an elliptical pattern with major axis about 9 feet in front of the sprinkler head riser. This indicates that the sprinkler risers should be located on a line 3 feet outside the plot boundary to provide the overlap necessary

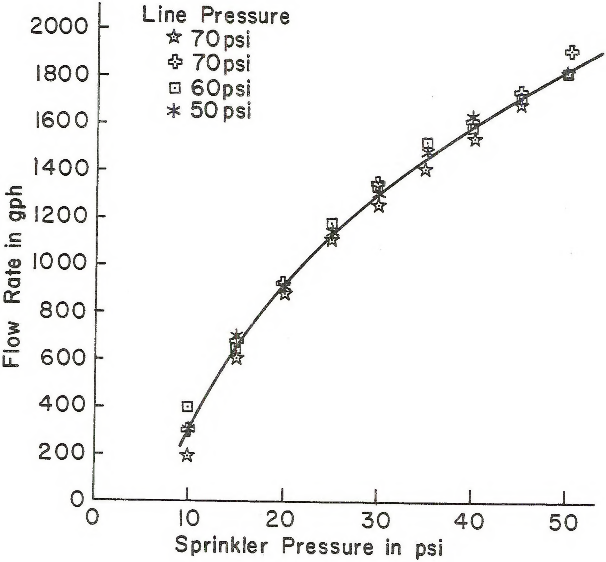


Figure 4. Sprinkler head pressure vs. flow rate for the field efficient simulator (FES).

11. A calibrated flow measurement device equipped with an analog or digital flow recorder is necessary to determine rates and volume of runoff. Small flumes such as the HS, the Parshall, the Replogle, and others are available that can either be purchased commercially or shop built locally. In either case, it is best to verify the calibration before placing the flume in operation and the rating curve should be checked periodically during field use.

Colorado State University Simulator (CSUS):

The original design of the Colorado State University Simulator was described by Holland (1969) as a permanent installation on a man-made watershed at the CSU campus in Ft. Collins, Colorado. In 1978, the U.S. Geological Survey (USGS), under contract to the BLM, modified this design to a 25-sprinkler portable unit that would apply simulated rainfall to plots approaching 4000 ft^2 in size (Fig. 8). These could be either small, natural watersheds or plots bounded by artificial barriers. Other modifications including a 7-sprinkler setup for use on 400 ft^2 plots (Fig. 9) and a 15-sprinkler setup for use on paired 0.02 acre plots (Fig. 10) have also been used.

Sprinkler risers for the CSUS were assembled as shown on Fig. 11. Table 5 lists the bill of materials for a single riser. Items 15 and 16, a 3/4" x 2½" nipple and a 3/4" x 3/4" x 1/4" tee, are needed only if the pressure regulator selected does not have a 1/4" tap for a pressure gage on the outlet side. Otherwise, these two items can be eliminated from the assembly.

Most tests to determine operating characteristics were run with the 25-sprinkler setup and a few of the tests were repeated with the 15-sprinkler setup. This is indicated in the discussion of each test.

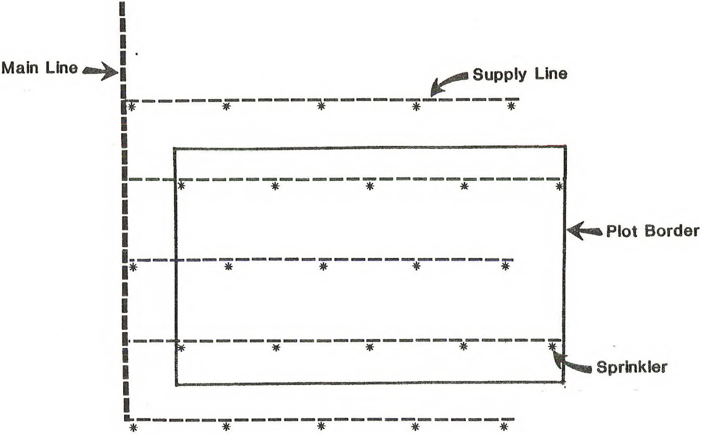


Figure 8. Physical layout of the 25-sprinkler Colorado State University Simulator (CSUS).

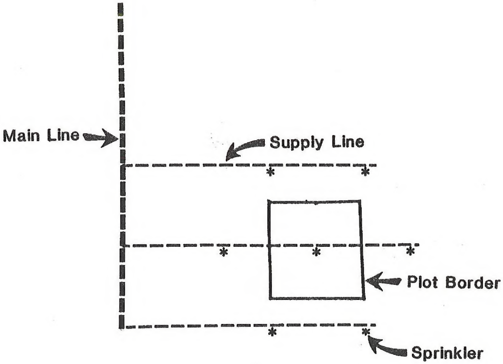


Figure 9. Physical layout of the 7-sprinkler Colorado State University Simulator (CSUS).

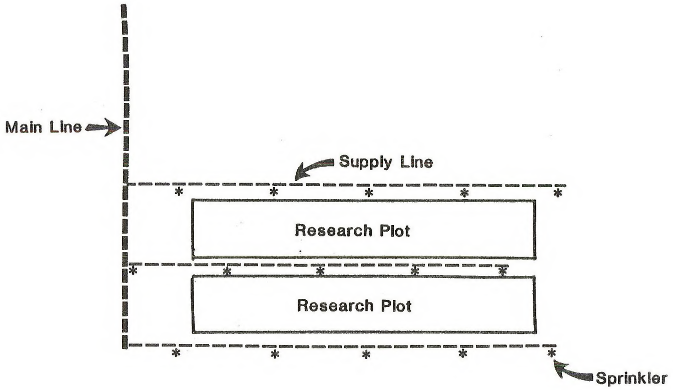


Figure 10. Physical layout of the 15-sprinkler Colorado State University Simulator (CSUS).

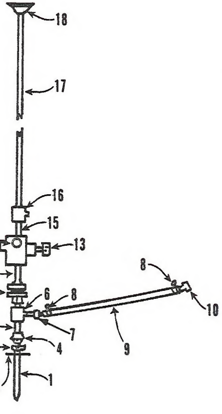


Figure 11. Schematic of CSUS sprinkler riser. Numbers refer to Table 5, Bill of Materials.

TABLE 5

Bill of Materials for Sprinkler Riser
Colorado State University Simulator

Item	Description	Source of Supply
1	Spike, 3/4" x 18" rolled steel	Shop made
2	Plate, 1/4" x 6" x 6"	Shop made
3	Male side of 3/4" pipe union	Local purchase
4	Female side of 3/4" pipe union	Local purchase
5	Nipple, 3/4" x 2"	Local purchase
6	Tee, 3/4" x 3/4" x 3/4"	Local purchase
7	3/4" HT with 3/4" hose shank	Local purchase
8	Hose clamp	Local purchase
9	Hose, industrial grade, 3/4" x 24"	Local purchase
10	Quick-connect coupler with hose shank, 3/4"	OPW Kamlok, Dover Corp., Cincinnati, Ohio
11	Adjustable ball fitting 3/4" x 3/4"	Spraying Systems Co., Wheaton, Illinois
12	Nipple, 3/4" x 2½"	Local purchase
13	Pressure regulator, 3/4"	Spraying Systems Co., Wheaton, Illinois
14	Pressure gage, liquid filled, 0-60 psi range	Marsh Instrument Co., Skokie, Illinois
15	Nipple 3/4" x 2½"	Local purchase
16	Tee, 3/4" x 3/4" x 1/4"	Local purchase
17	Pipe, 3/4" x 108"	Local purchase
18	Sprinkler head, 3/4", Mdl. 78C	Rain Jet Corp., Burbank, California

Flow Rate: We measured flow rates of individual sprinkers at sprinkler pressures of 10, 15, 20, 30, and 40 psi. We also tested a single sprinkler at intermediate pressures. The line on Fig. 12 is the average flow rate for a number of sprinklers and the plotted points are the results of the test on a single sprinkler. I believe that the deviations of the points from the line was caused by fluctuations in the supply line pressure during a run. The pressure regulators on the sprinkler risers apparently cannot compensate for fluctuations in supply line pressure. This emphasises the importance of maintaining a constant supply line pressure once a simulator run has begun.

Areal Distribution: Areal distribution was measured by a network of non-recording rain gages on and surrounding the research plot. When these tests were conducted the interest was in operational characteristics with a simulator rainfall application rate of about 2.5 inches per hour (iph). Therefore, tests were made with sprinkler head pressures ranging from 26 to 33 psi. The supply line pressure ranged from 55 to 70 psi.

Areal distribution under these conditions was very uniform. The standard error for catch in the rain gage network averaged about 0.02 inch with a minimum standard error of 0.016 inch and a maximum of 0.030 inch. The maximum occurred during a run in which the average wind velocity averaged more than 9 miles per hour during the test.

Application Rate: A theoretical application rate based on the CSUS construction geometry and using the Thiessen polygon method can be calculated by the formula:

$$I = 0.2782\ Q \qquad [1]$$

where I is the theoretical application rate in inches per hour and Q is the single-sprinkler flow rate in gallons per minute. The theoretical application rate, scaled from the relationship shown on Fig. 12, is shown on Fig. 13 as a solid line. The circles on Fig. 13 are calculated from the results of rain gage catch during simulator tests. The two lower circles at 31 and 33 psi are data from runs during which the wind velocity averaged 9.3 and 6.6 mph, respectively. I have no explanation for the high flyer of 2.83 iph at 31 psi.

Results of these tests indicate that it may be possible to vary the rainfall application rate on the research plot between 1 and 3 iph by changing the sprinkler pressure. Additional tests should be run to confirm this.

Drop Size Distribution: The flour pan method (Laws and Parsons, 1948) was used to determine drop size distribution. The first tests that were run indicated a distribution in which the drops were about one-half the size of natural rainfall. These results were reported in personal communications and during formal presentations. Later review of the procedure showed, however, that the first tests did not separate the larger drops into narrow enough size gradations. This was corrected and additional tests were run with a greater range of large size sieves.

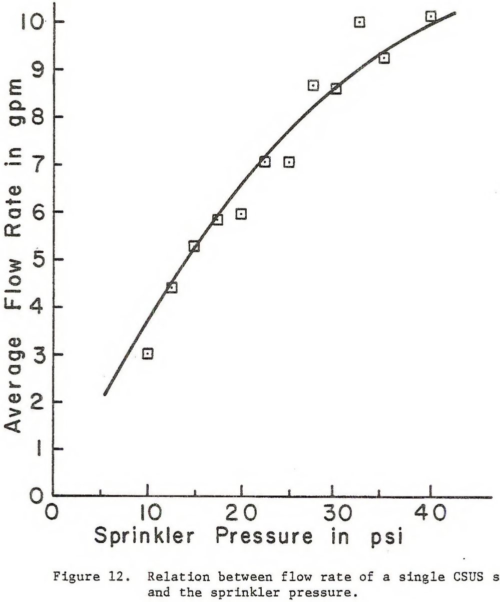


Figure 12. Relation between flow rate of a single CSUS sprinkler and the sprinkler pressure.

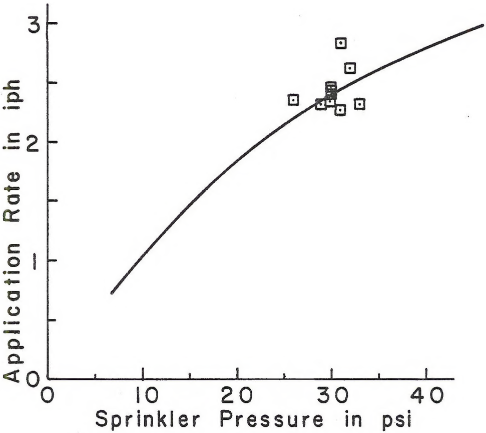


Figure 13. Application rate of the CSU simulator. The curve was scaled from Figure 12.

Results of the last tests are shown on Fig. 14. These data were taken with sprinkler head pressures at 22 psi producing an application rate of about 2 iph. This was the only test made using the additional sieves to determine drop size distribution because the summer field experiment was designed to use an application rate of 2 iph. Previous work, however, indicated that drop size increased as sprinkler head pressure decreased. Additional tests should be run to define the drop size distribution at sprinkler head pressures ranging between 10 and 40 psi.

Kinetic Energy: Kinetic energy produced by the CSUS operating with an application rate of 2 iph was calculated from data from Fig. 14 and was based on the assumption that the drops fell 4 meters.

Kinetic energy produced by the CSUS was 25.4 ft-lbs/ft^2/inch of rainfall. This was 54% of the kinetic energy of natural rainfall at 2 iph intensity. Simulator kinetic energy at intensities less than 2 iph should approach the kinetic energy of natural rainfall at the same intensity. However, simulator kinetic energy of the CSUS will not exceed about 70% of that of natural rainfall because the fall distance of the simulator is not great enough for the larger drops to reach terminal velocity.

Wind Effects: Studies of wind effects on simulator performance were conducted only with the 25-sprinkler setup. I assumed that wind would affect the uniformity of the areal distribution during a simulator run and that this disturbance could be measured by the increase in the standard error of measurement in the rain gage network catch. These data are shown on Fig. 15. With the 25-sprinkler setup, the sample standard error ranged between about 0.015 and 0.020 inch until the average wind velocity reached about 6.5 mph. The standard error increased with increasing wind velocity above 6.5 mph. There was some indication, but not enough data for confirmation that wind effects were less if the wind direction was parallel to the long axis of the simulator.

Tests were not run with either the 15-sprinkler or the 7-sprinkler setup. However, I believe that the wind effects are inversely related to the number of sprinklers in the simulator because of the overlap provided by additional sprinklers. Until further tests are made, I suggest that both the 15- and 7-sprinkler CSU simulators will be adversely effected when average wind velocity is greater than 5 mph during a simulator run.

Water Use Efficiency: Water use efficiency of the CSUS can be described in two ways. The first is to compare the calculated volume of water required to apply a given depth to a plot of specified dimensions to the actual volume used by the simulator to apply the given depth. This comparison is made on Table 6. In making these comparisons I assumed a single 45- x 75-foot plot for the 25-sprinkler setup, two 12- x 72.5-feet plots for the 15-sprinkler setup, and one 20- x 20-foot plot for the 7-sprinkler setup. The 25-sprinkler setup is the most water efficient, but it requires the greatest amount of water. The 15-sprinkler setup is

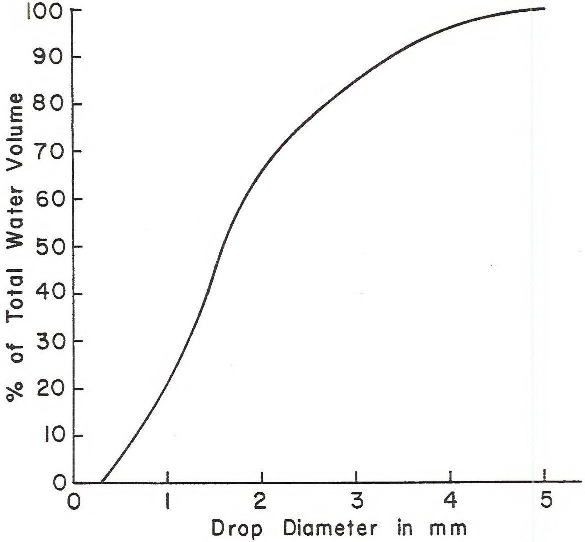


Figure 14. Drop size distribution of the CSU simulator applying rain at 2 iph.

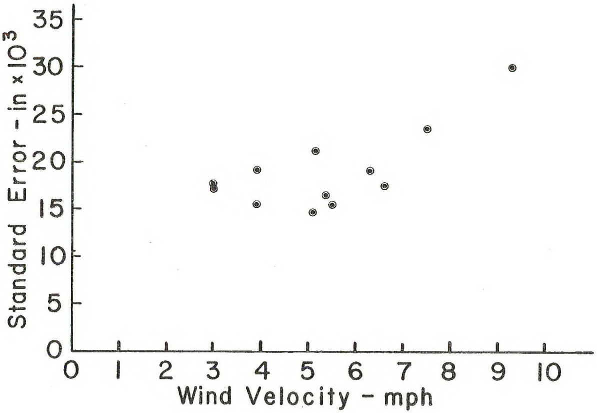


Figure 15. Average wind velocity during CSUS run and standard error of raingage catch.

only slightly less efficient, and it requires only 60% as much water for a given depth as the 25-sprinkler. The 7-sprinkler setup requires the least water, but it is also much less efficient.

The second assessment of efficiency was made by assuming a 3-foot buffer strip surrounding each plot. This buffer must be wetted the same as the plot in order to prevent lateral migration of infiltrated water from the plot. These results are shown in Table 7.

Comments: 1. I will reiterate the desireability of purchasing quality components to be used in simulator assembly. Such components will increase the cost of the simulator, but will result in ultimate savings by minimizing the number of malfunctions during runs; thus, reducing the personnel costs of salaries, travel, and transportation incident to repeat runs.

2. Simulated rainfall application rates can be varied between 1 iph and about 3 iph by regulating sprinkler head pressure.

3. The drop size distribution of simulated rainfall is smaller than natural rainfall at all intensities.

Table 6. Theoretical and actual volume of water required for application on a simulator plot.

Simulator Setup	1" Depth			2" Depth			3" Depth		
	Theo. Vol.	Actual Vol.	Eff.	Theo. Vol.	Actual Vol.	Eff.	Theo. Vol.	Actual Vol.	Eff.
	gal.	gal.	%	gal.	gal.	%	gal.	gal.	%
25-Sprinkler	2100	5550	38	4200	10700	39	6300	15900	40
15-Sprinkler	1100	3330	33	2200	6450	34	3250	9540	34
7-Sprinkler	250	1550	16	500	3000	17	750	4450	17

Table 7. Minimum and actual volume of water required for application on a simulator plot.

Simulator Setup	1" Depth			2" Depth			3" Depth		
	Theo. Vol.	Actual Vol	Eff.	Theo. Vol.	Actual Vol.	Eff.	Theo. Vol.	Actual Vol.	Eff.
	gal.	gal.	%	gal.	gal.	%	gal.	gal.	%
25-Sprinkler	2575	5550	46	5150	10700	48	7725	15900	49
15-Sprinkler	1490	3330	45	2980	6450	46	4470	9540	47
7-Sprinkler	420	1550	27	845	3000	28	1265	4450	28

4. The kinetic energy of simulated rainfall will vary from about 40% of that of natural rainfall at 3 iph to about 70% of that of natural rainfall at 1 iph. The simulated kinetic energy at an intensity of 2 iph is about 55% of the kinetic energy of natural rainfall at that intensity.

5. Water use efficiency for the CSUS varies from about 30% for the 7-sprinkler setup to about 50% for the 25-sprinkler setup. The 15-sprinkler is only slightly less efficient than the 25-sprinkler setup, and it uses only 60% as much water per run. These efficiencies may change if sprinkler head and plot configurations other than those shown in Figs. 8, 9, and 10 are used.

Recommendations: 1. Test the CSUS for areal distribution and drop size distribution at application intensities between 1 and 3 inches per hour and under a range of wind conditions.

2. Test a hybrid simulator assembled using the risers of the FES on the outside lines of sprinklers and the risers of the CSUS on the interior lines. In theory, this would increase the efficiency of a 25-sprinkler setup to about 70% and of a 15-sprinkler setup to over 90%. These efficiencies would be attained because the outside lines of sprinklers would be applying water in a 180° pattern and would operate at a much lower flow rate for a given intensity. For example, at an intensity of 2 iph, the FES individual sprinklers operate at a flow of 1.75 gpm whereas the CSUS sprinklers operate at a flow of 7.05 gpm.

Another advantage of the hybrid configuration is that the FES sprinklers will introduce larger drops into the distribution and thus, increase the simulator kinetic energy.

This suggestion is predicated on the assumption that the FES sprinkler risers can be located in a position that will result in uniform areal distribution over the research plots. This may be difficult with a 25-sprinkler setup, but may be attained with a 15-sprinkler setup.

Field Operations

Testing and Preplanning: Quality field data require adequate performance by all simulator components and ancillary equipment. Before a field season begins, each component and piece of equipment should be tested to assure acceptable performance.

Sprinkler heads and pressure regulators can present operation problems. Each riser, regulator, and sprinkler should be carefully inspected for physical damage and plugging from debris in the water supply. They should be disassembled and inspected for corrosion of the metal parts and deterioration of the seals. Frequently, bits of rust, sand, paint chips, etc., partially plug the sprinkler outlet holes and the problem can be detected only by careful inspection. Each riser should be tested individually at different sprinkler head pressures to confirm the relationship shown in Fig. 4. Any riser deviating from this curve should have either the pressure regulator or the sprinkler head inserts replaced and then retested. It is particularly important to test each riser at a pressure corresponding to the application rate specified in the experimental design. For example, if the experiment specifies an application rate of 2 iph, the risers should be checked at 22 psi pressure to make certain the flow rate is about 7 gpm. Simulator areal and drop size distribution can only be consistent if each sprinkler has the same operating characteristics.

Finally, the simulator should be assembled and run to determine if all components will function as a unit. This test will detect problems with the pump, the water filter, the water meter, the hoses and connections, etc. Repairs and adjustments can be made during a trial run without interfering with field data collection.

Preplanning will result in a certain amount of redundancy so that spare parts and components will be available as replacements for failures in the simulator. Recommended spares include sprinkler heads and inserts, pressure regulators, basic plumbing fixtures, and hoses and hose connections. I also recommend that field equipment include a mounted pipe vise and complete tool boxes for both plumbing and mechanical repairs.

Field Operations: Simulator operation in the field requires a number of steps as follows:

1. A simulator site is selected by considering criteria specified in the experimental plans.

2. The plot outlet at the point of lowest elevation is determined by use of an engineering transit or level. The outlet should be as near as possible to the mid-point of the lower plot border.

3. A transit base station is established by a known distance and direction from the plot outlet.

4. The location of all sprinkler risers, rain gages, plot borders, etc., are determined by measuring distance from the transit base station and deviation from an established base line.

5. As each point is determined by distance and direction from the transit base station, the ground surface elevation is found by use of an engineering level and a surveying rod. These will provide enough points to determine the topographic features of each plot and to draw contour maps. I used an assumed elevation for each plot and did not tie all plots to a common datum plane. However, plots can be roughly tied to a common datum plane by use of an anaroid barometer (surveying altimeter). Such an instrument is accurate within a few feet of elevation which should be adequate for plots several miles apart unless a precise measure of the difference in elevation is important.

6. Plot borders can be constructed in various ways. They can be made of sheet metal, lumber, ditches, natural micro-watershed boundries or combinations of these. The purpose of the borders is to prevent runon from outside the plot and to direct the plot runoff into a flow measuring device. I used a combination of sheet metal borders on the plot sides and drainage ditches at the upper and lower ends. A graded ditch was constructed at the upper end to intercept upslope runoff and direct it away from the plot. Another graded ditch at the lower end directed plot runoff into a measuring flume located near the center of the plot at the point of lowest elevation. The side borders were 16 gage metal cut 6 inches wide and 8 feet long. The upper edge was rolled about 1 inch to to provide some structural stability and as a safety feature to prevent cuts while handling. We used a concrete saw with a 1/4-inch wide blade to follow a chalk line and cut a groove 2 to 3 inches deep in which the metal borders were placed. The concrete saw was modified by:

a) Changing the pulley ratio to provide less blade speed, but more torque to prevent the engine from lugging and stopping.

b) Extending the axle so the rear wheel did not track behind the blade and press the groove closed.

c) Installing a handle on the front so that the saw could be pulled by an assistant as well as pushed by the operator.

I found that the concrete saw worked effectively in soils ranging from rocky, sandy, glacial till to wet, sticky, gumbo mud. In all cases, the saw worked best when the soil was dry.

The metal strips were worked into the grooves with a sawing motion and the strips were overlapped about 3 inches. The overlaps were held in place by driving 1- x 2-inch surveying stakes inside and outside the plot. The border strips were sealed by compacting the soil against the metal on the inside and the outside of the plot.

The installation of the metal borders and digging the ditches created loose soil that could be carried into the sampling station by runoff and thus, give erroneous estimates of plot erosion. To prevent such soil movement, the soil surface along the side borders and in the ditches was sprayed with a soil binder. I used Aero-Spray 52 Binder produced by American Cyanamid Company and purchased in 450 pound drums. The binder was mixed with equal parts of water and applied with ordinary garden sprinkling cans. The binder was applied at a rate that soaked all soil particles and penetrated 1/8 - 1/4 inch into the soil. After drying there was little or no visible erosion during runoff.

7. Runoff can be measured by any one of a number of flume designs. Any flume with a maximum capacity between 30 and 50 gallons per minute should be adequate. Supercritical flumes, because they are self-cleaning, are recommended for studies in which sediment is enough of a problem to deposit in the flume throat and affect the rating curve. If supercritical flumes are not available, care must be taken to keep the flume swept clear of sediment, and sediment sampling must be done at a point before any deposition has taken place. Gage height can be either determined visually at intervals or recorded with a water stage recorder. I used Belfort FW-1 water level recorders with the chart drive geared for one revolution per hour, and the float wheel geared so that a 0.5-foot rise in the flume equalled one traverse on the chart. Both of these are standard options and require no special modification of the recorder.

8. Rainfall amount, application rate, and areal distribution is measured by a network of nonrecording rain gages. Any watertight container such as tin cans or glass jars can be used as rain gages. However, I found fewer tabulation errors when direct reading gages were used. I used plastic, wedge-shaped Tru-Chek gages. In a previous experiment, I found this design to be the most accurate of several inexpensive rain gages.

The number of rain gages necessary depends upon the simulator being used, and the accuracy specified in the experimental design. As a rule of thumb, I recommend a network with uniform distribution containing twice as many rain gages as there are sprinklers in the layout.

9. A water meter to measure total use is not essential equipment. However, it provides a continuous check on simulator performance and, when compared to the rain gage catch, it provides an estimate of simulator efficiency from run to run. If a water meter is used, the inlet and outlet should be the same diameter as the main supply line to prevent head loss. It is also useful if the water meter has not only a totalizer for volume used, but also a rate meter that indicates instantaneous flow. The rate meter aids in detecting fluctuations during a simulator run.

10. A water filter, while not essential to simulator operation, can prevent many problems with pressure regulators and sprinkler heads. The filter should be placed in the main supply line between the pump and the water meter, if one is used, or between the pump and the simulator. The inlet and the outlet should be the same diameter as the supply line and the filter screen should have as large a mesh as possible to prevent head loss. I used both a 16 single mesh and a 50 double reinforced mesh screen without significant head loss. Even with the filter in line, it was necessary to periodically inspect the filters in the pressure regulators and the orifices of the sprinkler heads to make certain they were not plugged with debris. The sprinkler heads should be inspected each time before the risers are set up. I found bits of rust, chips of paint, weed seeds, and other material that plugged one or more of the outlets on sprinkler heads.

11. An auxiliary pump is not essential if the water supply truck is equipped with a PTO driven pump of sufficient capacity. However, I found that a 500 gpm trailer mounted pump provided much more flexibility because the water truck was not dedicated to direct simulator operation and the truck could continue to haul water while the simulator was running.

12. Portable A-frame shelters of 2 x 4 lumber covered with sheet plastic were used at each plot outlet to cover and protect the water level recorders and observers during simulator runs. These shelters were about 6 feet maximum height and length. They were easily portable and made the observers work much more comfortable.

13. The water supply was stored in flexible bags 14 feet wide and 26 feet long made of either hypalon or butal rubber. Three-inch diameter pipe boots were installed on the bag bottom as near the edge as possible at the center of one end and at the center of one side. A 2-inch diameter vent tube, 36 inches long, was installed in the top center. The pipe boots were used for both filling and emptying the bags, so 3-inch suction hose was threaded through the boots into the bag. The suction hose was equipped with quick-connect couplings.

The water bags were designed for 5000-gallon capacity, but field experience found that 4000 gallons was the maximum volume they could hold safely. There were problems of major seams failing, punctures by cactii spines, and leaks caused by abrasion during use. In addition, the bags would creep or roll during filling unless they were placed on nearly level ground.

Flexible storage bags placed on the ground created many difficulties. I suggest exploring alternate storage such as rigid, trailer mounted tanks or flexible bags on a flat-bed trailer that could be leveled at the site. This would solve some of the problems of lifting, moving, and handling an awkward piece of equipment.

14. To operate, flumes must be placed in a pit with the flume top at a lower elevation than the plot outlet. These pits are 1 to 2 feet deep,

depending on the flume design. The flume outlet must not be submerged during operation so some method for the disposal of runoff water is required. I used graded ditches from the flume pit bottom, a distance long enough to provide free outflow at the terminal end. These ditches were easily dug by hand on rangeland sites with plot slopes 5% or greater. However, on flat slopes, these ditches were sometimes several hundred feet long which precluded hand digging with limited time and personnel. In these cases, the ditches were machine dug at a considerable saving. At times, I rented a mechanical ditcher which was operated by members of the field crew and at other times I hired a contractor who furnished a machine and operator. Another option at sites where mechanical ditchers are not available or where long ditches are not possible would be a sump pit below the flume from which a small pump could dispose of the runoff water.

15. Average wind velocity for any period of time can be determined with a totalizing anemometer. For consistent comparisons, the anemometer should be at the same distance from the ground each time it is set up. I installed it with the axis of the rotating cups 3 feet above the ground surface.

16. Table 6 is a list of supplies and equipment recommended for simulator field operations.

Table 6. List of Supplies and Equipment Recommended for Simulator Field Operations.

Quantity	Item	Comment
1 ea.	Engineering Transit w/Tripod	
1 ea.	Engineering Level w/Tripod	
1 ea.	Leveling Rod	
2 ea.	Circular Rod Levels	These are used not only with the leveling rod, but also to quickly adjust the sprinkler risers to vertical alignment.
1 lot	Stake Tacks	
1 lot	Wire Stake Flags	These should be in a variety of flag colors so use can be color-coded.
1 lot	2 x 2 x 14 Surveying Stakes	
1 lot	1 x 2 x 14 Surveying Stakes	
2 ea.	100' Non-metallic Measuring Tapes	
1 ea.	100' Metallic Measuring Tape	
2 ea.	10' Steel Pocket Tapes	
2 ea.	6' Steel Ranging Poles	
1 lot	Engineers Field Level Books	These are useful not only for leveling notes, but also for permanent field observations and daily journals.
1 set	Mechanics Tools	
1 set	Plumbers Tools	
1 set	Carpenters Tools	
1 ea.	Mounted Pipe Vise	

Table 6. Continued

Quantity	Item	Comment
1 lot	Picks, Shovels, Spades	
1 ea.	3' Carpenters Level	
2 ea.	1' Carpenters Levels	
2 ea.	Bullseye Levels	These are useful for leveling the flume in the pit.
1 ea.	25' x 35' Heavy Duty Tarpaulin	This is spread on the ground to protect the water storage bag from abrasion and puncture. One tarp is required for each bag used.
1 ea.	Electric Drill, 3/8"	
1 ea.	Inverter, 12V DC to 120V AC.	This is used to operate electric hand tools.
1 ea.	Soldering Iron, 120V AC	

I have a few general observations in conclusion. Rainfall simulators have many limitations in the way rainfall is applied, in the size of the simulator plots, and in the amount of kinetic energy that is produced. Search of the literature will reveal a hundred, or more, different simulators, each of which is designed to solve one or more of these limitations, but none of which solves them all. There is no simulator that duplicates natural rainfall amount, intensity, energy, and temporal variation. These disadvantages must be recognized when planning a rainfall simulation study.

In spite of the problems invloved, rainfall simulators are the only tools that will provide what is needed (rainfall), where it is needed (at specified locations), when it is needed (during specified seasons; at specified times of crop, land, or livestock management, or at specified plant growth stages). Rainfall simulation is a useful procedure that will result in valuable information when it is used with knowledge of its limitations and care in the interpretation of the results.

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